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Risk-Based Decision Support of Water Resource Management Alternatives

OPERATIONS RESEARCH CENTER OF EXCELLENCE
TECHNICAL REPORT DSE-TR-0721
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December 2006

The Operations Research Center of Excellence in supported by the
Assistant Secretary of the Army (Financial Management & Comptroller)

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Executive Summary

This report describes a risk-based decision support system for designing and managing large-scale water resource projects. A model is presented that combines a new risk assessment methodology with traditional decision-making tools to enable systems engineers to capture the full spectrum of operational risks during the design process.

Enhancing public welfare through the deliberate management of water resources is vital for every society. Pollution, overuse and consumption challenge a society's ability to develop and sustain water supplies for municipal, agricultural, industrial, and recreational use while protecting fisheries and wetlands. Water resource management decisions are complex and involve risk. This project identifies a risk taxonomy to help managers identify where those risks are and their severity. These risk factors provide the foundation for a multi-attribute utility decision support tool for managers and policymakers.

Quantifying the risks in competing courses of action is an essential first step. The risk taxonomy identifies 13 risk factors that comprise the physical, logical, and environmental domains. Physical factors are the tangible components of the system. Logical factors encompass the cognitive functions of the system, including such "soft" qualities as *agility* and *self-synchronization* – the ability to organize and synchronize from the bottom up – both key factors in sustaining a management plan. Finally, environmental factors make up the setting in which the system exists, and includes not only weather-related issues, but also the role of well-intentioned humans and those who intend harm. Attributes of the essential risk elements are viewed in terms of utility and drive the decision process through traditional multi-attribute utility analysis. The result is a set of feasible alternatives that is both risk-based and value-focused for the decision maker to consider.

The project is presented in the context of the Susquehanna River Basin that spans three states in the United States, with management interests at the state, regional, and national levels. The Susquehanna River is the sixteenth largest river in the United States and its tributaries drain 27,510 square miles. The project builds on work supporting the Susquehanna River Basin Commission's decision on managing the14-mile-long Conowingo Pool near the river's terminus.

This project was conducted for the NATO Advanced Research Workshop held in Istanbul, Turkey, from 12 to 16 October 2006. The workshop brought together 60 scientists and engineers from 22 NATO, NATO Partnership, and NATO Dialogue counties to address critical issues of water resource management that may threaten the political stability of regions with scarce water resources.

The main body of this report will be published in 2007 as a chapter in the book, *Wastewater Reuse – Risk Assessment, Decision-Making and Environmental Security*, by Springer Science and Business Media, Dordrecht, the Netherlands. It will be included in the NATO Security through Science series on Environmental Security (Series C).

About the Authors

Dr. Paul West is an Assistant Professor in the Department of Systems Engineering at the United States Military Academy at West Point, New York. He holds a Ph.D. in Systems Engineering and Technology Management from the Stevens Institute of Technology, as well as Master of Technology Management, Master of Business Administration, and Bachelor of Science degrees. His research interests include the architecture and operation of network-centric systems and the study of human-like behavior in computer-generated environments.

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Acknowledgements

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Chapter 1. Managing Large-Scale Water Resources

Demand for water grows as populations increase and new uses are found and prioritized. Water management infrastructure is costly to build in both time and money and must be sustainable for decades in the face of uncertain future requirements. Comprehensive water management planning must account for risks not only to physical elements of the system, but also to those elements that enable the system to meet changing needs and uncertain times.

Managing the Conowingo "pond" in the northeast United States highlights these challenges. The pond, a 9,000-acre (3,642-hectare) reservoir spanning 14 miles (22.5 kilometers) in Pennsylvania and Maryland, was created in 1928 with the completion of the Conowingo dam. [1] The Conowingo system gradually outgrew its intended purpose of solely providing hydroelectric power, and by the dawn of the 21st Century a complex system of users was dependent on the pond for its survival. Key stakeholders faced this new reality in 2002 with the creation of the Conowingo Pond Workgroup of the Susquehanna River Basin Commission. Their goal was to develop a resource management plan that provides for current and future users while meeting existing state and federal regulations.

This complex decision scenario is used to illustrate how a new, comprehensive risk-based decision support system can help decision makers choose between competing alternatives in both short-term and long-term projects. The approach is to quantify exposure to sources of operational risk, identify measures for assessing their effects, and determine the utility of various alternatives based on the decision maker's sensitivity to each of the risk categories. The result is an analysis of alternatives that reflects the decision maker's assessment of risk and willingness to accept it.

1.1. The Conowingo Pond Problem

The Conowingo Pond region is at the southern terminus of the Susquehanna River Basin, shown in Figure 1, which spans much of Pennsylvania and portions of New York State to the north and Maryland to the south.

Figure 1. The Conowingo Pond Region [1]

The Conowingo Dam is one of four hydroelectric projects on the lower Susquehanna River. All are regulated by the Federal Energy Regulatory Commission (FERC), whose oversight includes minimum flow requirements to maintain a reliable energy source. However, as populations and uses grew, so did competing requirements. By 2002, the Conowingo Pond was a source of water for:

- Conowingo Hydroelectric Station
- Muddy Run Pumped Storage Facility
- Peach Bottom Atomic Power Station
- Baltimore, Maryland, municipal water supply
- Harford County, Maryland, municipal water supply
- Chester Water Authority (southeast Pennsylvania and northern Delaware)
- Recreational use
- Sustained stream flows downstream of the dam.

The Muddy Run facility stores water pumped from the Pond during low energy requirements to resupply the Pond during high-use periods. The Peach Bottom facility requires a constant source of water for coolant, and a sustained stream flow is essential to supply downstream users, support fish and wildlife, and control salinity.

1.2. Risk and Risk Management

Risks exist at all stages of a system's life cycle – from establishing the need and developing the system concept, to designing and producing the system, to deploying and operating the system, to its retirement. Opportunities for failure are ever present. This paper focuses on operational risks that can be "designed out" early in the system development process.

Risk is often expressed in terms of expected value – the probability and severity of adverse effects. [2] It is measured as the combined effect of the probability of occurrence and the assessed consequences given that occurrence. [3] Identifying risks comes in the form of determining sources of risk events and situations under which they may occur. [4] From a system operations point of view, the management of those risks can be defined as, "the process of identifying, assessing, and controlling risks arising from operational factors and making decisions that balance risk costs with mission benefits." [5] U.S. Department of Defense guidance for risk management in the acquisition process specifies that, "Program risk includes all risk events and their relationships to each other. It is a top-level assessment of impact to the program when all risk events at the lower levels of the program are considered." It continues, "One of the greatest strengths of a formal, continuous risk management process is the proactive quest to identify risk events for handling, and the reduction of uncertainty that results from handling actions." [6]

Several risk taxonomies have been proposed to capture risk events and their relationships to each other (see West [7] for a detailed comparison). However, these tend to focus on specific applications or remain broad in scope. A taxonomy is described below that addresses operational risk factors from a system-level view that forms the basis of a risk-based decision support tool.

For a taxonomy to be useful to the decision maker, it must be comprehensive, measurable, and relevant. These attributes, according to Keeney and Raiffa, [8] have the following qualities:

- It is *comprehensive* if, by knowing the level of an attribute in a particular situation, the decision maker has a clear understanding of the extent that the associated objective is achieved.

- It is *measurable* if it is reasonable to both

    - Obtain a probability distribution or to assign a point value, and

    - Assess decision maker's preferences for different attribute levels.

- It is *relevant* to the particular courses of action under consideration.

1.3. Endnotes

[1] Workgroup, Conowingo Pond (2006). Conowingo Pond Management Plan. Harrisburg, PA, Susquehanna River Basin Commission**:** 153.

[2] Haimes, Yacov Y. (1998). Risk Modeling, Assessment and Management. New York, John Wiley & Sons, Inc.

[3] Blanchard, Benjamin S. and Fabrycky, Wolter J. (1998). Systems Engineering and Analysis. Upper Saddle River, NJ, Prentice Hall.

[4] Sage, Andrew P. (1992). Systems Engineering. New York, John Wiley & Sons, Inc.

[5] Army, United States (1998). FM 100-14: Risk Management. Washington DC.

[6] Smith, Edward A. (2001). "Network-Centric Warfare; What's the Point?" Naval War College Review **Winter 2001**.

[7] West, Paul (2003). Dynamic Risk Management of Network-Centric Systems. Ann Arbor, MI, ProQuest.

[8] Keeney, Ralph L. and Raiffa, Howard (1976). Decisions with Multiple Objectives. New York, John Wiley & Sons.

Chapter 2. A System-Level Risk Taxonomy

A "systems" approach to risk management requires that the scope of risk assessment be extended to account for a comprehensive range of factors. Such a framework must be sufficiently robust to apply to all systems while being adequately specific to provide a quantifiable assessment. The taxonomy described below is based on a decomposition of total system risk to a point at which relevant measures can be obtained. The complete structure is shown in Figure 2 and described in detail in the following sections.

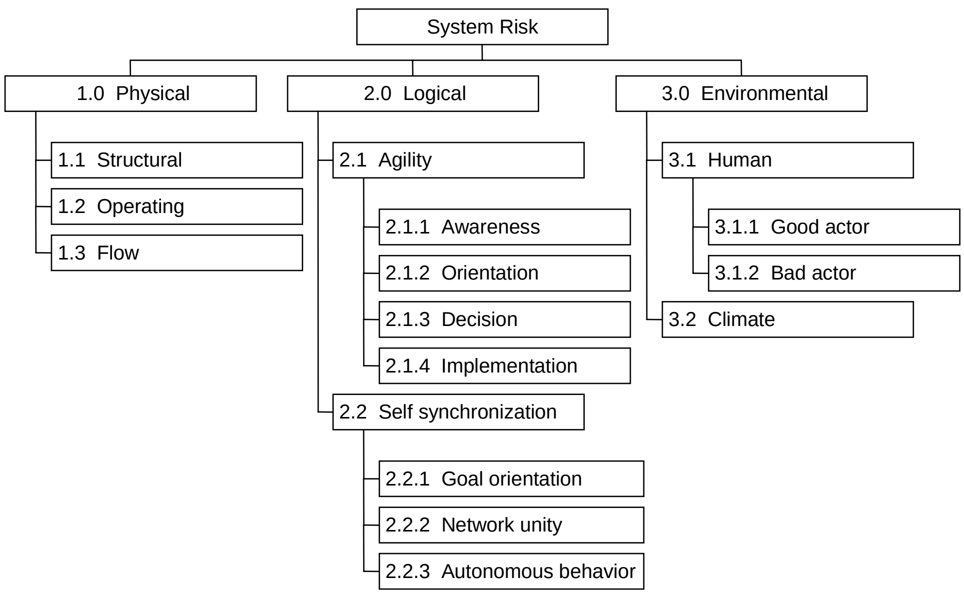

Figure 2. System Risk Taxonomy

2.1. Risk Domains

Top-level elements that contribute to total system risk are the physical, logical, and environmental domains in which a system operates.

- *Physical* factors are the tangible components of the system.
- *Logical* factors include all cognitive functions, whether by software or human intervention.
- *Environmental* factors are external factors that affect system operation.

2.1.1. Physical factors

These consist of the *structural* components that normally do not change during the life of a system, *operating* components that process material to make the system function, and *flow* components, which are the materials processed through the operating components.

In the Conowingo Dam system, the dam itself is a structural component; turbines, flood gates are related equipment are operating components; and water and lubricants are flow components.

2.1.2. Logical factors

Agility and *self-synchronization* are primary drivers of the logical domain.

Agility is the process by which a superior information position is turned into a competitive advantage. It is the quality that enables a system to efficiently adapt to changing conditions, and is essential for long-duration systems such as water management systems to avoid obsolescence. Agility is characterized by:

- *Awareness,* the degree of comprehending the common operating picture.
- *Orientation,* the degree of comprehending the situation given a level of training, education and experience.
- *Decision,* the degree to which cognitive comparisons can be made. It is the "irrevocable allocation of resources to affect some chosen change or the continuance of the status quo."
- *Implementation,* the degree to which an action can be taken as a result of a decision.

Self synchronization is the ability of a well-informed system to organize and synchronize complex activities from the bottom up.

- *Goal orientation* is the degree of comprehending the desired end state – the result, or effect – of the process. It is the *decision maker's intent* and includes not only the mission, but also key tasks to be accomplished so that sub-elements understand the intermediate goals and can act autonomously when unexpected situations arise. Intent is a clear,

concise statement of what the system must do to succeed. It does *not* include the *why*, the *how*, or the level of acceptable *risk* related to the process.

- *Network unity* is the degree to which nodes in the system can function *collectively* to achieve the goals of the system by maintaining the integrity of the network. This provides the unity of effort.

- *Autonomous behavior* is the degree to which nodes in the system can function *independently* to achieve the goals of the system given a clear understanding of the mission, a common operating picture, clear goal orientation, and a clear set of rules to bound the decision space.

2.1.3. Environmental factors

These are the external factors, both human and non-human, that can affect the system.

Human factors include all interactions with people, regardless of motivation.

- *Good actor* considerations include the degree to which well-intentioned humans may adversely affect the functioning of the system. These include incorrect responses to events, carelessness, and accidents.

- *Bad actor* considerations include the degree to which mal-intentioned humans may adversely affect the functioning of the system. Bad actors include disgruntled or co-opted insiders, criminals, terrorists, or hostile nation states.

Climate is the degree to which non-human elements adversely affect the system. These include weather, heating, ventilation and air conditioning (HVAC), and natural phenomena such as earthquakes, floods, and volcanoes.

2.2. Mapping Stakeholder Needs to Risk Domains

Stakeholder involvement is critical to the success of the systems decision process. [9] Stakeholders ensure that decision makers have the appropriate frame for a decision, and provide reliable and credible information. Stakeholders comprise the set of individuals and organizations

that have a vested interest in the problem and the solution. [10] Besides decision makers, stakeholders can include customers, system operators, system maintainers, bill payers, owners, regulatory agencies, sponsors, manufacturers and marketers. [11] Stakeholder input is generally gained through interviews, focus group meetings, or surveys. The Conowingo Pond Workgroup consisted of representatives of 27 stakeholder groups who met in 17 sessions over a four-year period. They identified the 11 major concerns shown in Table 1.

Table 1. Conowingo Stakeholder Concerns

Hydroelectric power generation	Multipurpose use benefits
Public water supply	Anadromous fish restoration
Upstream consumptive use	Upstream reservoirs
Minimum flow requirements	Environmental resources
Minimum dissolved oxygen	Cooperative management
Summer minimum pond levels	

These concerns reflect the interests of a disparate group of stakeholders and may conflict. For example, concerns for upstream reservoirs would be less of an issue if hydroelectric power generation did not require a water flow. Reconciling these concerns is accomplished by value modeling, in which both qualitative and quantitative models are developed. The result is a coherent method for assessing solution alternatives. In the proposed risk-based approach, the risk taxonomy provides the core for the quantitative value model, while the qualitative model is developed directly from stakeholder input.

The modeling and assessment that follows is illustrative and was not conducted with the Conowingo Pond Workgroup. It is intended to show how the methodology can be used to support decision-making for complex water management projects.

2.3. Endnotes

[9] Parnell, Gregory and West, Paul (2006). Systems Decision Process. Decision Making for Systems Engineering and Management. G. Parnell and P. Driscoll. New York, John Wiley and Sons.

[10] Sage, Andrew P. and Armstrong, James E., Jr. (2000). Introduction to Systems Engineering. New York, John Wiley & Sons, Inc.

[11] Trainor, Timothy and Parnell, Gregory (2006). Problem Definition. Decision Making for Systems Engineering and Management. G. Parnell and P. Driscoll. New York, John Wiley and Sons.

Chapter 3. Value Modeling

3.1. Qualitative Value Modeling

Solution design is a deliberate process for composing a set of feasible alternatives for consideration by a decision maker. [12] It follows, but overlaps with the problem definition phase of the system design process, and it is essential that stakeholder needs, wants, and desires are understood for feasible alternatives to be developed.

Qualitative value model development consists of the following five steps:

- *Identify the fundamental objective*. This is a clear, concise statement of the primary reason for addressing the problem. For the Conowingo project, it may be stated as to "develop a long-term management plan that ensures water availability for municipal, industrial, and recreational users and sustains the natural environment."
- *Identify functions that provide value*. These may include "provide hydroelectric energy" and "provide municipal water supply."
- *Identify objectives that define value*. Objectives provide a statement of preference, such as "minimize salinity encroachment" and "maximize summer pond levels."
- *Identify value measures.* Value measures indicate how well a candidate solution meets an objective. For example, salinity may be measured in the concentration of salt in the water in parts-per-million (ppm) or in percentage. Sea water, with salinity of about 35,000 ppm, may also be considered as being about 3.5 percent salt. Another measure may be "practical salinity units," in which sea water is about 35 and fresh water (1000 ppm) is 1. The choice of measure depends on how well it informs the decision maker.
- *Discuss the value model with key stakeholders.* Feedback and buy-in on the appropriateness of the model is critical.

3.2. Quantitative Value Modeling

Quantitative value models identify how well an overall candidate solution attains stakeholder values. They consist of two basic parts: a weighting mechanism to prioritize competing attributes, and a utility function that indicates how much utility an attribute's value has, given the decision maker's preferences. Utility functions are used to convert values with different units of measure to a single scale, which can then be summed across all measures to attain an overall alternative utility score. The concept is that the alternative that provides the greatest utility to the decision maker is the preferred choice.

A risk-based decision support system considers the decision maker's risk preference for each value. Risk preferences are generally categorized in one of the four shapes shown in Figure 3.

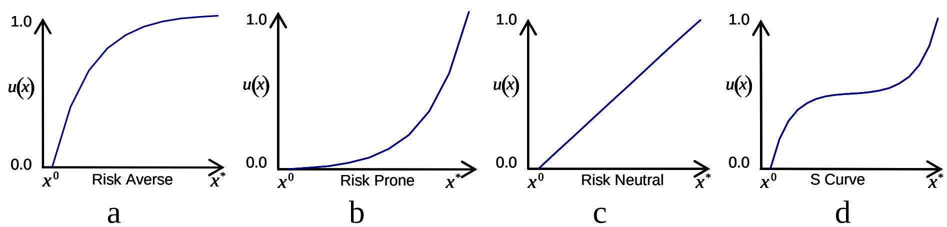

Figure 3. Utility Curve Shapes

The curve at Figure 3a shows a sharp increase in utility when risk is low, but less utility as it increases – indicating a risk-aversion. Figure 3b shows a risk-taking attitude, where more utility is gained when the risk is greater, while Figure 3c shows risk neutrality. Figure 3d indicates a change in risk tolerance – there is an aversion to risk at low levels, but a willingness to accept higher risks.

The idea of risk and utility is often discussed in terms of decisions involving risk and reward. Consider a choice between two lotteries. In the first, there is a 99 percent chance of receiving \$10 and a 1 percent chance of receiving nothing. In the second, there is a 60 percent chance of receiving \$100 and a 40 percent chance of receiving nothing. A risk-averse person may choose the first option since there is a greater chance of getting something. A risk-taking person may choose the second, since the potential reward is greater. Someone with an S-curve preference may choose the first option initially, but if the reward were sufficiently great may choose the riskier option.

The weighting mechanism for the risk-based decision support system is derived from the risk taxonomy described earlier. Total system risk is aggregated in the top-level node. Each tier beneath it reflects the degree each element contributes to the higher level. When summed, the risks associated with the physical, logical, and environmental domains represent total system risk. Therefore, a *local weight* (LW) can be assigned to each of the three domains that when summed equals one, as shown in Figure 4. Individual weights must be elicited from key stakeholders. The same strategy applies to each sub-level progressively down the tree. A final, *global weight* (GW) value for each pathway is found by multiplying all local weights along a pathway. This process reveals the distribution of total risk from all 13 risk factors. The sum of all global weights will also be one.

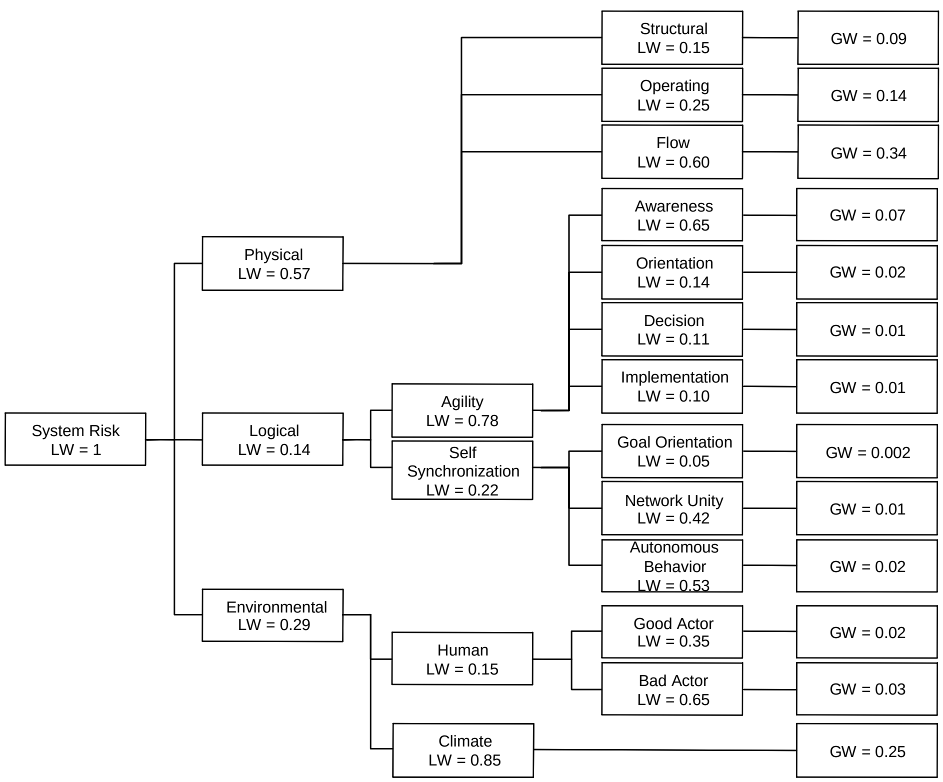

Figure 4. Risk Taxonomy as a Value Hierarchy

3.3. Endnotes

[12] West, Paul (2006). Solution Design. Decision Making for Systems Engineering and Management. G. Parnell and P. Driscoll. New York, John Wiley and Sons.

Chapter 4. Analysis of Alternatives

Quantifiable measures based on stakeholder values are developed for each of the lowest-level factors. Alternative solutions are then developed that reflect qualitative and quantitative stakeholder values. Alternatives are scored in each of the 13 risk areas based on empirical or simulation-based data.

4.1. Determining Alternative Utility

Standard multi-attribute utility (MAU) methods are then used to determine total utility scores for each alternative. Figure 5 illustrates the process for two possible alternatives: Maintain Level Storage and Automatically Waiver Levels Outside of Limits.

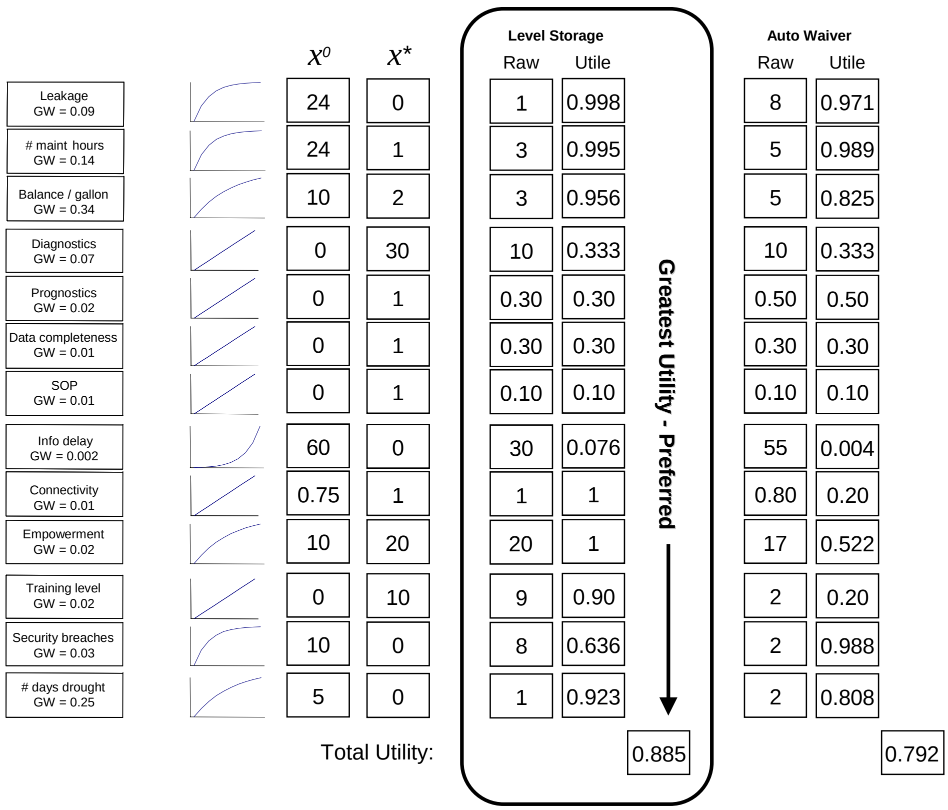

Figure 5. Multi-Attribute Utility Analysis of Alternatives

Stakeholders determine the minimum acceptable threshold value (x^0) and the ideal value (x^*). The local utility of an individual score (called a *utile*) is determined by where the raw value falls along the utility curve for that measure. The utile value is then weighted by the risk factor weight to determine the weighted utility score for that measure and alternative. This is

done for each measure, then the weighted utility scores are added to find the total utility of the alternative. The alternative that has the most *utility* for the decision maker should be the preferred choice.

Raw scores are found for each measure and alternative. A raw score of 1 is shown for the first measure. This is very near the desired value of 0 and therefore has a high degree of utility for the decision maker. Utiles are normally determined mathematically based on where they fall on the curve. In this case, the raw value is 99.8 percent of the way between the minimum acceptable threshold of 24 and the ideal value of 0, given the shape of the utility curve. Although this number is high, the weight assigned to that measure by stakeholders is low (0.09). The local utility of this measure, then, is also low (0.08982).

The total utility of the first alternative sums to 0.885, while that of the second is 0.792. This tells the decision maker that based on key stakeholders' risk assessment – derived from the risk taxonomy, their risk tolerance, and their minimally acceptable and ideal values – the Level Storage alternative provides the greatest overall utility and should be the preferred choice.

4.2. Sensitivity Analysis

Overall utility scores are the products of many values – often subjective – gathered from stakeholders. The analyst must be confident that minor variations in initial assessments would not alter the decision outcome. It is therefore important that a follow-up analysis be conducted to ensure that the model is free of "acceptable" variations within the parameters. It was noted that the raw score of first measure of the Level Storage alternative was near ideal (99.8 percent), yet a very low weight (0.09) resulted in low utility (0.08982). Sensitivity analysis seeks to find if a reasonable variation of the weight would result in a meaningful change in utility, and therefore alter the recommendation.

Analysis techniques are well documented and are not reproduced here. However, in all cases they either seek to either identify a point of indifference where the decision would change, or, given limits, determine if the indifference point falls within those limits.

Chapter 5. Summary

Water management decisions affect diverse and changing populations, and enhancing public welfare through the deliberate management of water resources is vital for every society. This paper presents a process for segmenting risk into a manageable set of factors that affect the operation of a system. This risk taxonomy provides a structure for assessing key stakeholder values to support management decisions.

This comprehensive risk assessment provides input for traditional multi-attribute utility analysis whereby otherwise feasible alternatives are evaluated by the total utility they offer stakeholders. The product is a values-based decision support tool to design and management complex projects that can contribute to the success of a water management plan.

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Appendix A: List of Symbols, Abbreviations and Acronyms

D	
DSE	Department of Systems Engineering
DTIC	Defense Technical Information Center
F	
FERC	Federal Energy Regulatory Commission
G	
GW	Global Weight
H	
HVAC	Heating, Ventilation, and Air Conditioning
L	
LTC	Lieutenant Colonel
LW	Local Weight
M	
MAU	Multi-Attribute Utility
N	
NATO	North Atlantic Treaty Organization
P	
Ph.D.	Doctor of Philosophy
ppm	Parts per million
U	
USMA	United States Military Academy

*This table is sorted alphabetically

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14. ABSTRACT
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